DOI 10.5162/EUROSENSORS2025/MP66

A Calibration Method for Spatial Localization of OPM Sensors Based on a Rigid Coil Array Framework

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Summary:

A calibration method based on a rigid coil array framework was developed for spatially localizing Optically Pumped Magnetometer (OPM) sensors in wearable Magnetoencephalography (MEG) systems. The proposed framework integrates multiple coils into a fixed geometric configuration, enabling precise validation of sensor positioning and enhancing the front-end registration process. By incorporating the Structural Similarity Index Measure (SSIM) as an optimization objective, the method significantly improves localization accuracy compared to conventional approaches. Simulation results demonstrated that the localization error was maintained below 3 mm, meeting the precision requirements for OPM-MEG registration. The rigid coil array structure effectively reduced random errors introduced by manual operations and tracking systems, providing a stable reference framework for aligning sensor coordinates with anatomical brain data. This work advances both theoretical and practical aspects of OPM-MEG calibration, offering a robust solution for high-precision sensor localization.

Keywords: OPM-MEG; sensor localization; rigid coil array; Biot–Savart law; Structural Similarity Index Measure (SSIM); magnetic field fitting; registration accuracy; spatial positioning; least-squares optimization.

Title

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Headlines

This study presents the design of a rigid structure capable of supporting a coil array, incorporating data preprocessing and nonlinear multi-parameter minimization. By using the Structural Similarity Index Measure (SSIM) as the objective function, the system accurately determines the spatial positions and orientations of sensors in OPM-MEG. This work provides both theoretical and hardware support for the frontend of OPM-MEG registration.

Background

Calibration of spatial sensors is a critical component in the registration process of wearable OPM-MEG systems, enabling accurate alignment between the sensor coordinate system and the anatomical coordinate system of the brain. Conventional fixation methods often suffer from insufficient stability and are susceptible to human-induced random errors during initial measurements. To address this limitation, a rigid framework for the sensor array is proposed in this study, which significantly reduces random errors and provides a more stable and reliable solution for subsequent sensor localization [1].

Description of the New Method or System

In previous studies, the use of coils for MEG registration typically involved attaching three or more coils directly onto the scalp or forehead. After fixation, a position tracker was employed to digitize both the scalp surface and the coil locations, thereby determining the spatial relationship between the coils and the subject’s head. However, this approach introduces substantial random errors, both during the coil attachment process and in the operation of the tracking system.To mitigate these sources of error, a 3D rigid support structure capable of holding an array of coils has been designed. This rigid coil array famework structure serves to fix all coils in a unified and stable configuration, providing a dedicated coordinate system for the coil array that supports more accurate and reliable MEG registration.

The rigid coil array framework structure is capable of accommodating up to 35 coils, with both the positions and magnetic moment orientations of the coils being fixed. The primary function of the helmet in this setup is to serve as a spatial reference. By rigidly attaching the helmet to the RCS, both the sensors and the coils are placed within a unified coordinate system. This configuration allows the spatial relationships between the sensors and the coils to be predetermined, enabling consistent and accurate localization within the shared structural frame. The rigid helmet is capable of accommodating up to 85 sensors. For detailed specifications and configuration, please refer to the relevant literature [3].

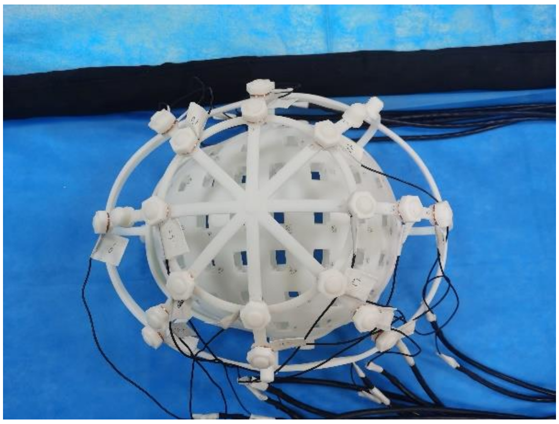

Fig. 1. Rigid Coil Array Framework Structure and rigid helmet

Results and conclusion

. Tab. 1: Experimental Results

Accuracy	Conventional	SSIM
1	2.96mm	2.21mm
2	2.79mm	2.53mm
3	2.12mm	1.99mm
4	2.79mm	2.13mm
5	2.94mm	2.58mm

In this experiment, 15 coils and 5 sensors were employed to evaluate the localization performance, with all procedures carried out under magnetically shielded conditions. As demonstrated in the corresponding figures and tables, the localization errors remained within 3 mm, thereby meeting the typical accuracy requirements for sensor-to-coil registration. Since the initial positions of the sensors were known a priori, all reported errors represent absolute deviations. The contribution of model-induced errors was negligible and therefore excluded from the analysis. Importantly, the use of SSIM as the objective function yielded consistently lower registration errors compared to those obtained using a conventional objective function, highlighting its effectiveness in improving localization accuracy.

Localization Principle

When the spatial extent of the current distribution is much smaller than the distance between the observation point and the current source, the Biot–Savart law can be approximated by the magnetic dipole model. This simplification is particularly useful for describing the far-field magnetic field generated by systems such as current loops or small permanent magnets. The magnetic field of a magnetic dipole at a point r\mathbf{r}r is given by eg. (1) [2].

$$B(\mathbf{r}) = \frac{\mu_0}{4\pi}\left[\frac{3(\mathbf{m}\cdot\hat{\mathbf{r}})\hat{\mathbf{r}}-\mathbf{m}}{|\mathbf{r}|^3}\right] \qquad (1)$$

Where, $B(\mathbf{r})$ is the magnetic field at a position $\mathbf{r}$ （T） μ_0 is the permeability of free space； $\mathbf{m}$ is the magnetic dipole moment （A·m^2） , defined as $\mathbf{m} = I\mathbf{A}$, with I denoting the current and $\mathbf{A}$ representing the vector area of the current loop; $\hat{\mathbf{r}} = \mathbf{r}/|\mathbf{r}|$ is the unit vector pointing from the dipole to the observation point; $r = |\mathbf{r}|$ is the distance from the dipole center to the field point.

$$f(\theta_s, \phi_s, x_s, y_s, z_s, k) = 1 - \mathrm{SSIM}(\mathbf{B}, \mathbf{B}^*) \qquad (2)$$

Where, $\mathbf{B}$ denote the magnetic field computed from the model， $\mathbf{B}^*$ represent the magnetic field measured by the sensor. The position of the sensor is represented in Cartesian coordinates as $[x_s, y_s, z_s]$, The orientation of the sensor's sensitive axis is represented in spherical coordinates as (θ_s, ϕ_s) ， θ_s is the polar angle measured from the positive zzz-axis, within the range [0,π]. ϕ_s is the azimuthal angle measured from the positive xxx-axis in the xyxyxy-plane, within the range [0,2π].

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